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FINAL TECHNICAL REPORT

to the
Air Force Office of Scientific Research
Attn: Dr. L. Sakell

AASERT Grant No. F49620-93-1-0476

Studies of Hypersonic Vehicle Flowfields

Covering the Period 9/1/94 through 8/31/96

Submitted by:

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November 1996

ABSTRACT

Here, we present the Final Technical Report on AASERT Grant No. F49620-93-1-0476 Studies of Hypersonic Vehicle Flowfields, in support of AFOSR Grant F49620-93-0064 "Studies Of Hypersonic Boundary Layer Behavior". The parent grant covered three interrelated research efforts: a study of the structure of hypersonic turbulent boundary layers and shock wave boundary layer interactions, a study of boundary layer transition at supersonic and hypersonic speeds, and the development and application of new optical techniques including filtered Rayleigh scattering and RELIEF to obtain multi-dimensional velocity and density data in the supersonic and hypersonic regimes.

2. PROGRESS

As part of our experimental program under AASERT Grant F49620-93-1-0476, a new high Mach number boundary layer facility was built (see Figure 1). This facility is designed specifically for the study of transition, turbulence and shock wave boundary layer interactions at supersonic and hypersonic Mach numbers. This tunnel, when operated with air as the working fluid, operates from Mach 2 to 8. It has a circular test section with a diameter of 229mm (9 in), with an overall length of 1.5m. A maximum temperature of 875K (1115F) at a maximum pressure of 10^7 Pa (1500 psia) is generated to allow running times of 2 to 3 minutes. The tunnel operating conditions give a Reynolds number range so that at the lowest Reynolds number the flow is laminar (even on the tunnel walls), and at the highest Reynolds number fully turbulent boundary layers are generated on a flat plate mounted in the test section. Even at Mach 8 a Reynolds number based on momentum thickness of about 12,000 is possible, with natural transition and a highly cooled wall. The key parts of the installation are a storage heater which consists of a coil of heavy-walled stainless steel pipe which is preheated electrically to the desired stagnation temperature, and air ejectors driven by the existing high pressure air supply which provide low back pressures. The tunnel can be run with air or other gases (the mass flow rates are relatively small). A complete description of the facility was presented at the 80th Supersonic Tunnel Association Meetings in May 1993.

As part of the tunnel installation, our high pressure piping system was upgraded and extended. A new ejector system was installed to provide low back pressures, and our Low Turbulence Variable Geometry (LTVG) Mach 3 facility was connected to it. Tests of the ejector system have been very satisfactory, and Reynolds numbers as low as 2.3 x 10^6/m have been achieved in normal operation of the LTVG. The Mach 8 facility was ready for its first trials in May 1995, and it has been fully operational since April of 1996.

We are now engaged in studying the flowfield generated by a generic hypersonic vehicle shape. This investigation will provide data on a complex three-dimensional flowfield which is expected to contribute new insight into the physics of shock-shock interactions, the generation of vorticity in compressible flows (by the action of pressure gradients acting on boundaries as well as by baroclinic torques, the surface pressure and heat loading, the steadiness of the flowfield and the onset of separation in high-speed three-dimensional flows. This detailed information on the flowfield behavior will also be used to generate an important test case for code validation. In the original proposal, we proposed a study of a delta wing with rounded leading edges at a 30° angle of attack (designated "Problem 7" in Abgrall et al. 1992). Following discussions with the Program Manager, Dr. L. Sakell, we have instead studied the flowfield around a 4:1 elliptical cone at Mach 8. This is the same body that is being used in computational transition studies by Thorvald Herbert at Ohio State University, and experimental transition studies by Steve Schneider at Purdue University. The experimental work has used flow visualization to provide preliminary information on the transition process over the forebody of the cone as a function of Reynolds number. The results to date are summarized in Figure 2.

3 ADDITIONAL ACTIVITIES

Under the aegis of the AFOSR/URI Aerothermochemistry Program we are developing the capability to conduct combustion experiments at Mach 3. That facility, the Princeton Supersonic Combustion Tunnel, uses the same heater, diffuser, cooler and ejector system as the Mach 8 facility. Therefore the addition of the hypersonic tunnel also represents a major factor in broadening the scope of our capabilities at Princeton. The design work has been completed, but the construction has been delayed until the preliminary combustion exeperiemnts in the pilot facility in the Guggenheim Combustion Laboratories have been completed.

Under the same grant, we are also studying a number of pre-mixed combustion experiments where the fluid mechanics is laminar. Preliminary work will be performed in the LTVG, once we have established that it is possible to operate that facility with laminar flow on the nozzle walls. The candidate flow is the laminar flow over a diamond-shaped airfoil, which, in the absence of combustion, can be computed very accurately. Comparisons with computations represent a cornerstone of this effort.

4. PERSONNEL

This grant has helped to support the work of Professors A.J. Smits, R.B. Miles and G.L. Brown, Dr. W.R. Lempert, and graduate students T.A. Nau, M.L. Baumgartner, Mark Huntley and undergraduate student W.C. Rowley (all US citizens). One MSE thesis was awarded, to T.A. Nau (see below).

5. PUBLICATIONS ACKNOWLEDGING GRANT F49620-93-1-0476

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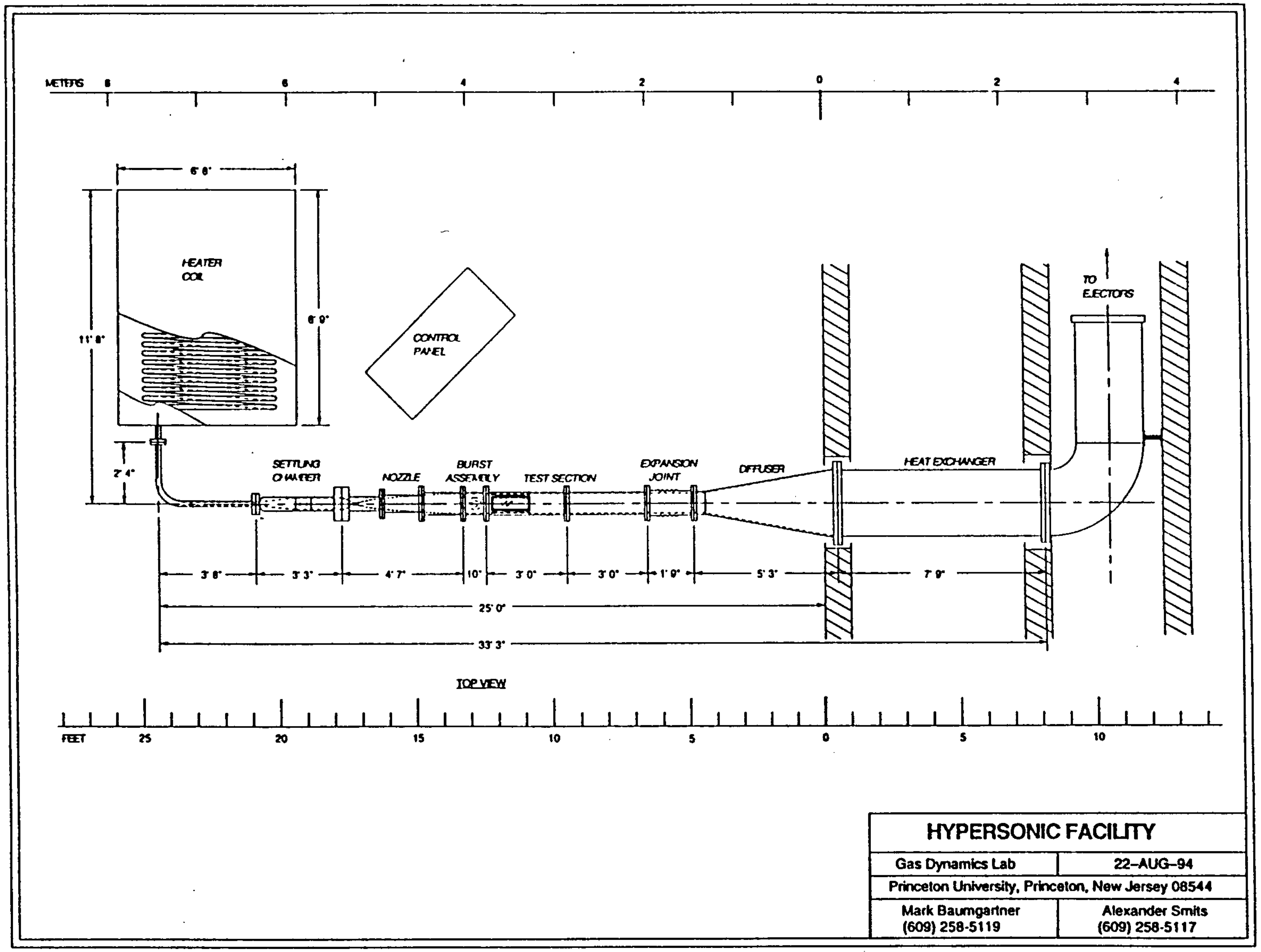
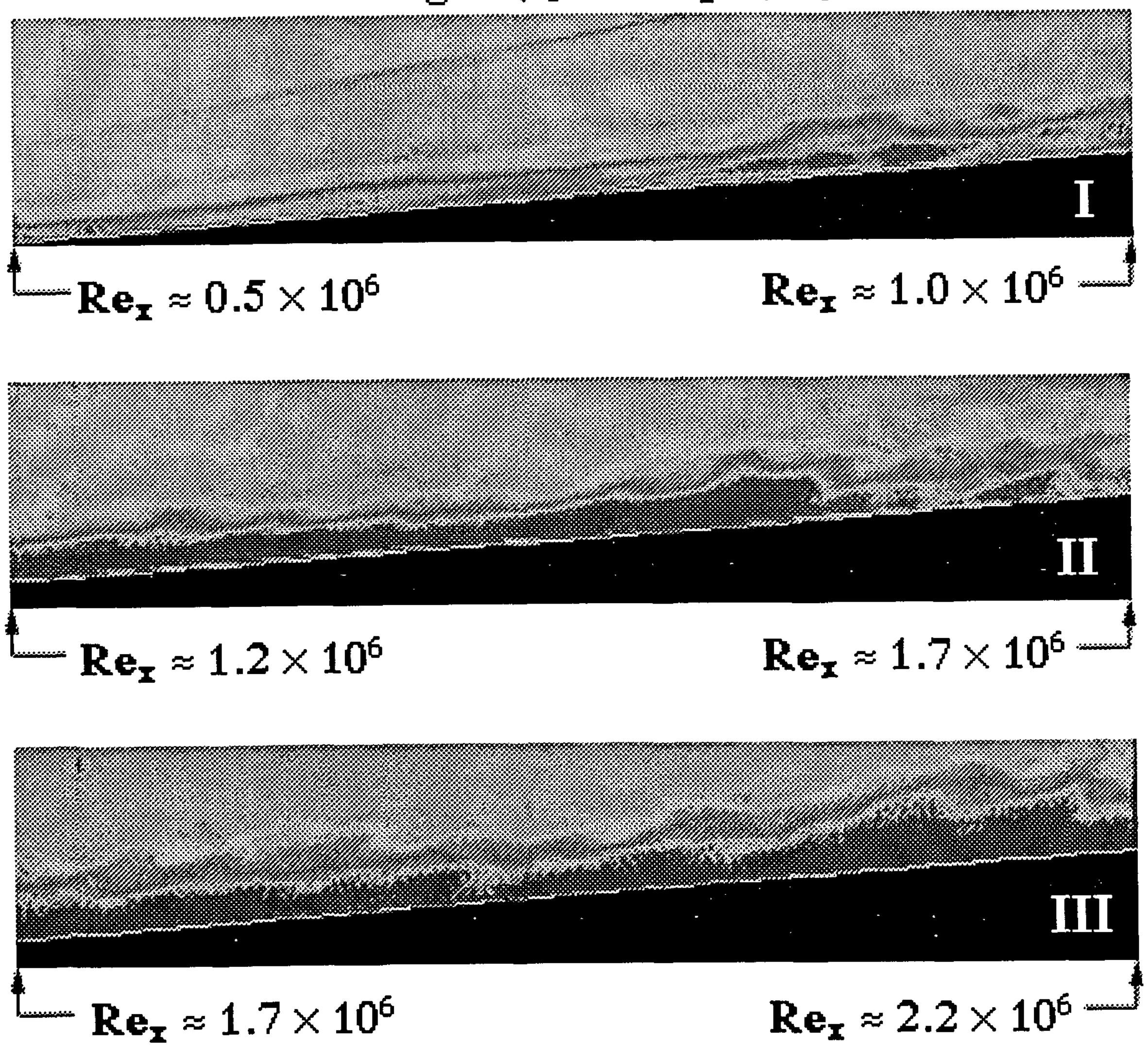
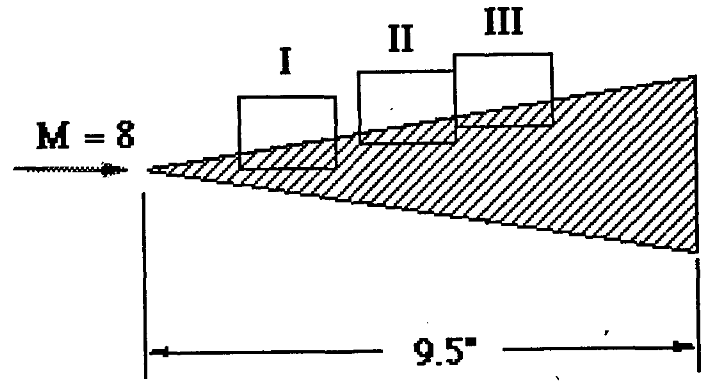


Fig. 1. Schematic of the hypersonic facility.

Transition Study on a 4:1 Elliptic Cone

Schlieren Images ($P_o = 900$psi, $T_o = 740$K)





Critical Reynolds Numbers

- **Computational**
  Huang et al., 4:1 **Elliptic Cone, M**=4
  $Re_x = 1.3 \times 10^5$ (**Crossflow**)
- **Experimental**
  Stetson, Axisymmetric Cone, M=8
  $1.5 \times 10^6 < Re_x < 4.0 \times 10^6$
  (**Secondary Mode**)

FIGURE 2.